PREDICTION OF FATIGUE PROPERTIES OF FORGED COMPONENTS:
INFLUENCE OF THE MANUFACTURING PROCESS

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Abstract. Fatigue life prediction of structures remains a difficult task. This is particularly true for hot-forged components. During the forging operation, the material is significantly hot-strained which induces changes of mechanical properties (e.g., yield stress, fatigue limit, …), microstructure, generation of residual stresses and cumulated plastic strains. An efficient fatigue life prediction requires the determination of the influence of these parameters on fatigue properties. Nevertheless the study of each parameter (evolution of the microstructure, cumulated plastic strain, …) by traditional fatigue tests campaigns is cost- and time- prohibitive.

In order to reduce the time necessary for fatigue life characterization, we are using a method, which has been developed the last few years. The efficiency and the reliability have already been shown by several research teams. The proposed method, so-called “self-heating”, allows to determine with a single test specimen the fatigue properties of the studied materials. The process influence on the fatigue behavior is accounted for by testing samples with a non-standard initial state and is representative of the manufacturing process. Various non-standard states are being studied with different deformation ratio (80% and 20%), different grain sizes (G=9 and G=5) as well as standard materials specimen with shot-peened or polished surface treatments.

1 INTRODUCTION

When developing a new hip prosthesis it is essential to guaranty an optimal level of mechanical strength that will minimize the risk of having an implant failure in vivo. In order to prevent such a risk, laboratory tests are done, in particular fatigue testing. Traditional fatigue test campaigns (e.g. staircase method) would require large sample sizes and testing time to accommodate the scatter associated with component fatigue test results. For this reason, high cycle fatigue (HCF) properties of orthopaedic implants is not commonly performed. In most cases, a minimum level of fatigue performance at only one stress level is evaluated by testing at least 6 specimens of the worst case design in agreement with US Food and Drug Administration guidance (FDA) and applicable standards [1-3]. Two configurations are usually tested: Proximal fatigue testing (ISO 7206-4) simulates a hip prosthesis properly fixed in the femoral bone and distal fatigue testing (ISO 7206-6) simulates the partial cemented loosening of a hip prosthesis (cf. figure 1).

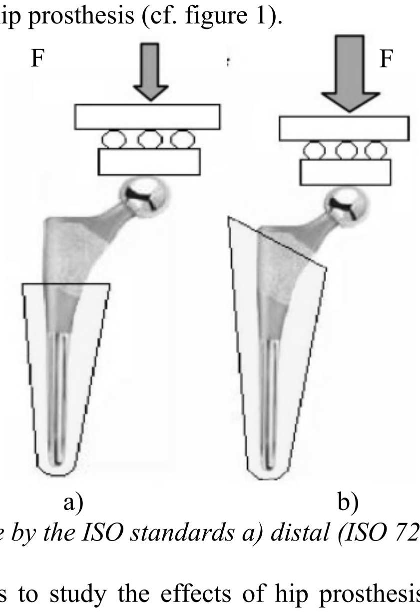


Figure 1: The two embedment define by the ISO standards a) distal (ISO 7206-6) and b) proximal (ISO 7206-4).

The objective of this work is to study the effects of hip prosthesis manufacturing process on finished goods High Cycles Fatigue (HCF) properties. Two steps of the process will be studied: forging and shot-peening. Nevertheless, in order to limit the time needed for fatigue test campaigns, the self-heating method will be used.

This method, developed these last years, allow to identify HCF properties with rapid tests and a low number of samples.

2 HIP PROSTHESIS MANUFACTURING

In this first part we will describe the raw material and the process used to manufacture the studied hip prosthesis. The manufacturing process transforms the material in a non-standard state. Non-standard states will be described in order to manufacture samples representative of these non-standard states then we will perform self-heating test to identify theirs HCF properties.

2.1 Description of the virgin material

The virgin material is an austenitic stainless steel, which has been developed for orthopaedic implants. Its chemical composition (cf. table 1) allows a good corrosion resistance. Its austenitic phase is stable with non-magnetic properties.

Table 1: Chemical composition of the raw material in weight percentage.

Fe	C	Cr	Ni	Mn	Mo	N	Nb
balance	<0.06	21.00	9.50	4.00	2.20	0.40	traces

Different tests were performed to determine the raw material mechanical properties, such as tensile test (cf. figure 2) or hardness (all stresses values, are normed by the yield stress).

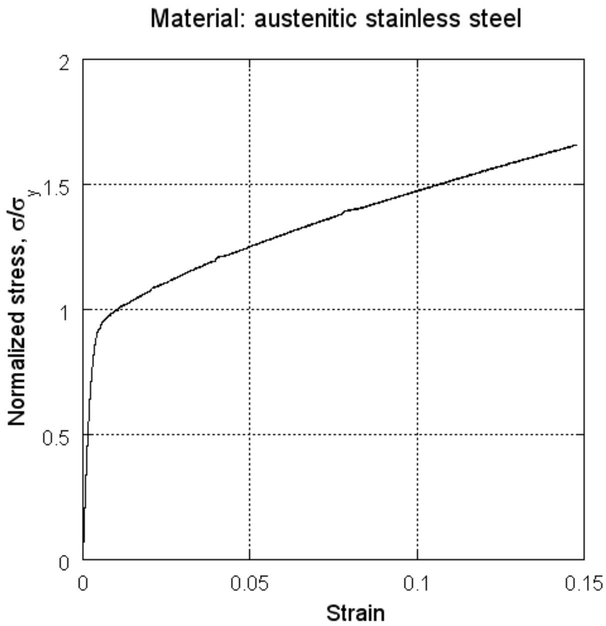


Figure 2: Stress/strain curve of the raw material, with stress normed by the yield stress.

The microstructure was observed by optical microscopy (cf. figure 3) and the component distribution by scanning electron microscope. A fine and homogeneous microstructure and grain size were observed. No carbides were observed when analyzing the raw material.

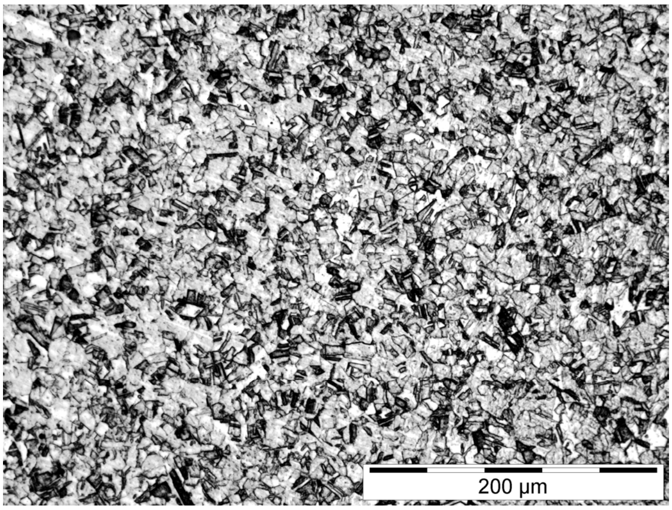


Figure 3: Optical micrographie of the raw material.

2.2 Description of the process

The manufacturing process of the studied hip prosthesis is composed of multipasshot-forging with different heating steps, a machining phase and a shot-peening surface treatment.

After the forging phases the non-standard state of the material is characterized by hot pre-strain. Figure 4 shows the distribution of hot pre-strain due to all forging processes of the hip prosthesis, which were calculated using finite element analysis. The strain scale is normalized, and non-homogeneous distribution of hot pre-strain can be observed. The pre-strain state has an impact on the mechanical properties of the material as showed in figure 5. A 80% hot pre-strain induces a 24% increase of the yield stress and a 23% increase of the hardness. These changes will influence the HCF properties.

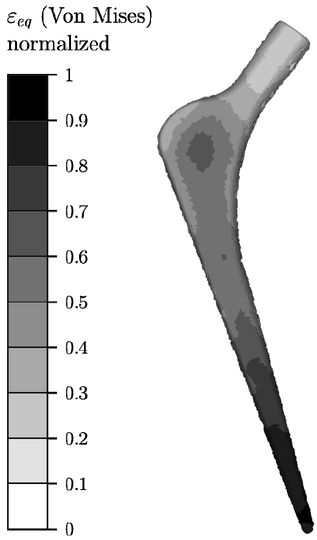


Figure 4: Pre-strain due to all forging processes of a hip prosthesis calculated using finite element analysis.

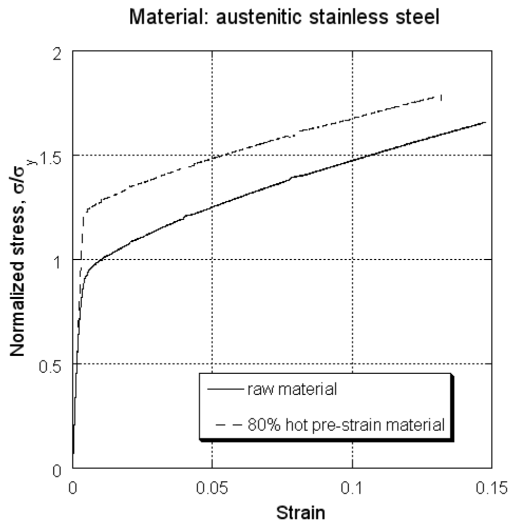


Figure 5: Comparison the stress/strain curves of the raw material and material pre-strain at 80%.

The non-standard state of the material obtained by shot-peening is characterized by compressive residual stresses on the surface of specimens and roughness. This surface treatment is well known for its benefit on HCF.

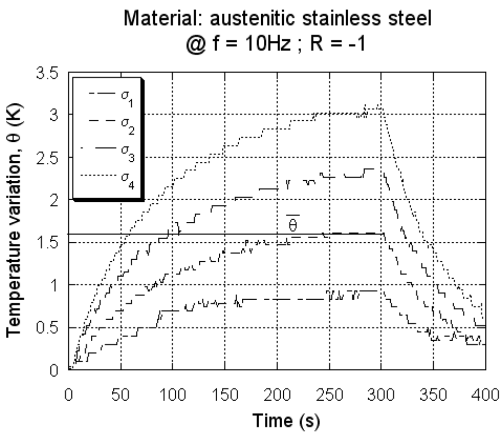
Only the effects of hot forging and shot-peening on HCF properties will be studied using self-heating method.

3 SELF-HEATING METHOD

This second part aims at presenting the self-heating method, which has been developed for many years [4-6]. First, the testing method will be presented, then, how to use the results. Finally, we will present a model, which makes the link between self-heating measurements and predicted fatigue strength.

3.1 Test description

Self-heating tests are done by applying cyclic load sequences to determine the steady state temperature $\bar{\theta}$ for different stress amplitudes Σ_0 (cf. figure 6). Then, as shown in figure 7, a self-heating curve can be drawn.



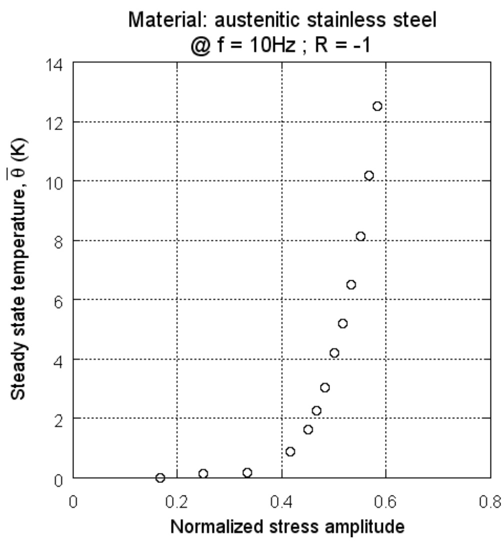
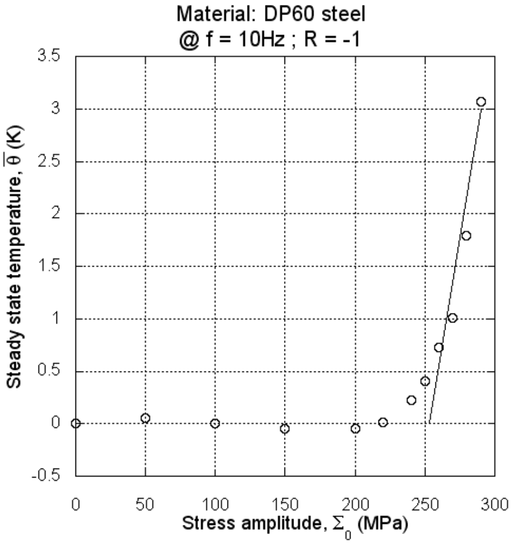


Figure 6: Evolution of temperature during cyclic loading.Figure 7: Self-heating curve

3.2 Result analysis

A graphical procedure is first used to “read” self-heating curves. The intersect between abscissa and the curve’s asymptote gives an estimation of the fatigue strength (cf. figure 8 and 9). This procedure has been validated experimentally for many materials.



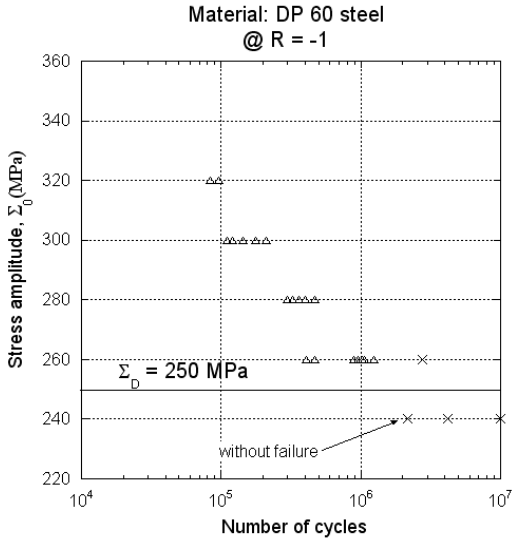


Figure 8: Graphical procedure.Figure 9: Fatigue strength determined on S-N curve.

3.3 Two scales models [7]

Models are based on the hypothesis that HCF damage is driven by microscopic plasticity, which is modelized by an Elementary Representative Volume (ERV) composed of elasto-plastic inclusions in an elastic matrix. Depending on how plasticity occurred in inclusions, one can adapt the model. Microplasticity can be explained by grain orientation or boundary or the presence of inclusions.

3.3.1 Determinist model:

This model considers that all inclusions have the same microscopic yield-stress σ_y^μ. The determinist model is described by the equation:

$$\bar{\theta} = \eta . f_r . \sigma_y^\mu . \left\langle \Sigma_0 - \sigma_y^\mu \right\rangle .$$

Where η is a constant and f_r is the frequency. If we consider that $\sigma_y^\mu = \Sigma_\infty$ then it can explain the experimental analysis result and allow to find the fatigue strength (cf. figure 10).

3.3.2 Probabilistic model [8-9]

In this model, a Weibull distribution is considered for inclusion’s yield-stress. The following equation describes the self-heating curve for the probabilistic model (cf. figure 10):

$$\bar{\theta} = \lambda . f_r . \Sigma_0^{m+2} .$$

Where λ is a constant and m the Weibull modulus. This model is used to identify the scatter in HCF.
Some methods permit to describe the entire S-N curve, using both models.

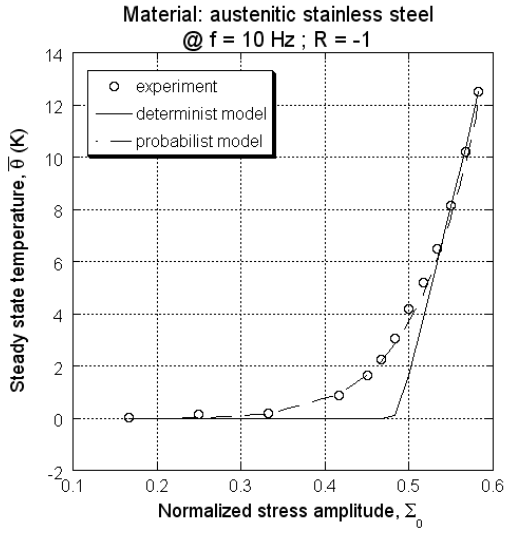


Figure 10: Self-heating modelisation.

4 INFLUENCE OF THE PROCESS ON HCF PROPERTIES

This third part deals with the influence of a non-standard state of the material on HCF properties. In order to save time, HCF properties were identified using the self-heating method. Two non-standard states were studied: after forging and after shot-peening.

4.1 Samples design

Testing samples design have to meet two criteria. First, to make data analysis easier, samples must be homogeneous in terms of section and material state. Second, the materials state of samples must be representative of the non-standard state obtained with the process.

The non-standard state of the studied hip prosthesis due to forging is characterized by hot pre-strain obtain by material flow between dies. Pre-strain in the forged hip prosthesis are not homogeneous, so we cannot use exactly the same process to manufacture samples. A finite element analysis of hot-rolling showed that pre-strain are homogeneous in the rolled part (cf. figure 11). We simulated heating according to the real process, and then by simulating hot-rolling, we calculated an homogeneous non-standard state close to a forged hip prosthesis. For manufacturing easiness, the pre-strain obtained by hot-rolling is 80%.

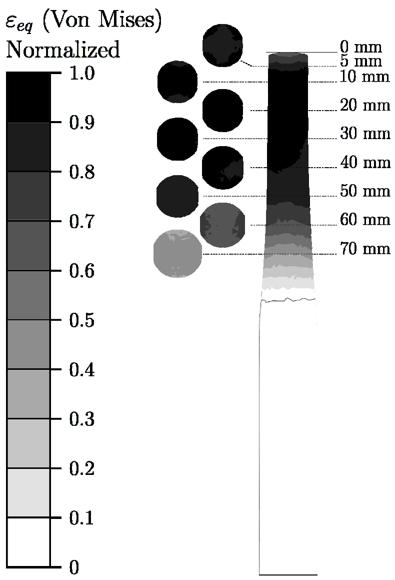


Figure 11: Finite elements analysis of hot-rolling.

For the non-standard state due to shot-peening, the surface treatment was applied directly on samples of the raw material. However, in regard of the size and number of samples the subcontractor could not guaranty the homogeneity of the process.

All samples have the same geometry (cf. figure 12), cylindrical with a 8mm diameter. This allows a sufficient Elementary Representative Volume.

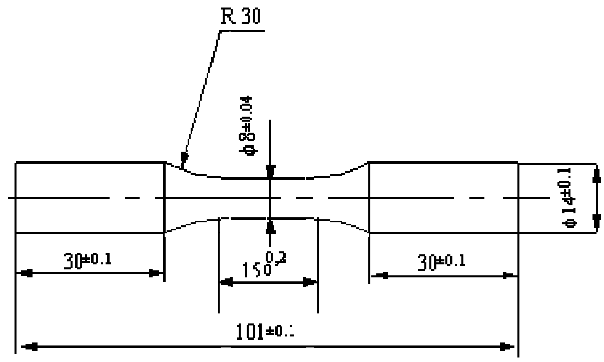


Figure 12: Samples plan (all dimensions are in mm).

4.2 Influence of hot pre-strain

The 80% hot pre-strain state has an influence on the self-heating response of the material (cf. figure 13). The fatigue strength was increased by 60%. The improved fatigue strength was expected following an increased yield stress.

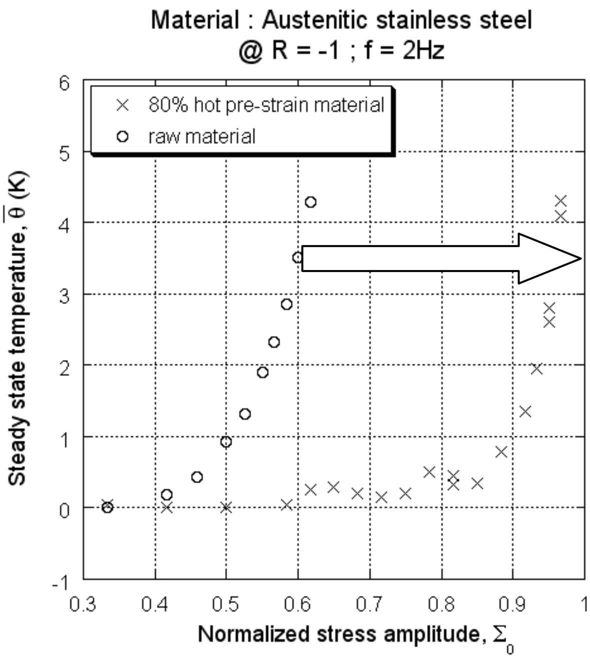


Figure 13: Influence of 80% pre-strain on self-heating.

4.3 Effect of the shot-penning

The shot-peened state shows scattered self-heating response (cf. figure 14). A deviation of fatigue strength prediction of 10% was observed.

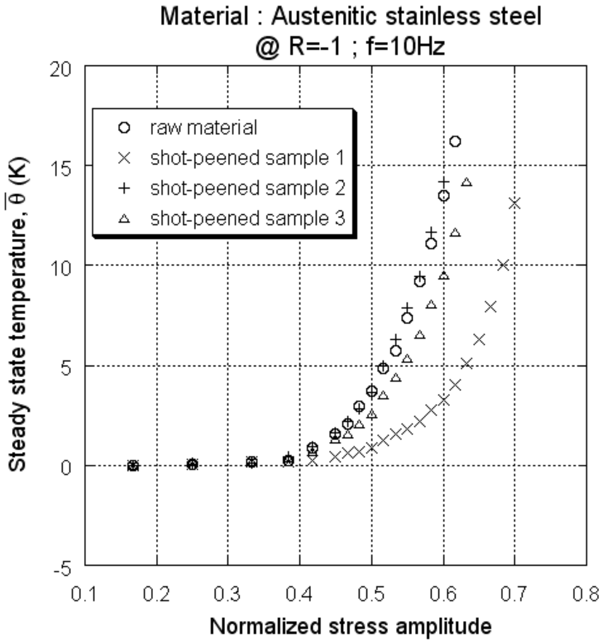


Figure 14: Influence of shot-peening on self heating.

5 SUMMARY AND CONCLUSION

We were able to reproduce material non-standard states of a forged hip prosthesis on samples. Using these samples, the self-heating method confirmed the benefit of forging on HCF. Only one pre-strain level has been tested yet, but different levels will now be tested in order to have a better understanding of this parameter and its influence on HCF. Heat-treatment after forging will also be studied.

Shot-peening process influence was also detected on self-heating curves, but the link with the fatigue strength has yet to be proven. We expect that surface loading provided by rotating-bending testing will emphasize the effect of shot-peening on the self-heating results

Acknowledgements

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